Scientific Investigations Map 3394 U.S. Department of the Interior U.S. Geological Survey Pamphlet accompanies map **CORRELATION OF MAP UNITS** LIST OF MAP UNITS **Squirrel Gulch andesite** Megabreccia, Proterozoic clasts dominant **Figure 15.** A, Geologic map of [Some unit exposures on the printed or plotted maps are too small to distinguish the sheet-like mass of flow-layered [Dotted unit-box boundaries indicate gradational welding or other emplacement contacts within eruptive units. Some major formation Sawatch-Range Ignimbrite (Erupted from Aetna Caldera) Volcaniclastic rocks color for unit identification. These units are labeled where possible; unlabeled units rhyolite (see B, C, photo 10.3), names are labelled. Some units of a formation are divided by emplacement type] are attributed in the database] Tbc Badger Creek Tuff interpreted as rheomorphic SURFICIAL DEPOSITS GLACIAL DEPOSITS lower Bonanza Tuff (unit Tbrr), Conejos Formation, Lower Units SURFICIAL DEPOSITS along upper Schoolhouse Gulch Upper outflow dacite Early lavas and proximal breccias (GG). Letter symbols mark Alluvium (Holocene) locations of GPS-located Main dacite Qm Colluvium (Holocene) outcrops and areas of monolithologic float inferred to reflect Plagioclase andesite Nonwelded dacite Landslide deposits (Holocene) immediately underlying bedrock: A, andesite; D, dacite; Intracaldera dacite fracture fill MIOCENE POSTCALDERA ROCKS Alluvial-fan deposits (Holocene) M, large blocks of andesite, in Andesite breccia matrix of nonwelded rhyolite Talus (Holocene) SEDIMENTARY ROCKS OF THE RIO GRANDE RIFT ZONE tuff; MBR, mega- and Volcaniclastic rocks Older alluvial-fan deposits (Pleistocene) meso-breccia of andesite rdup° Tdu Tdua∵ Main intracaldera rhyolite Jacks Creek Volcano (~34.5 Ma) blocks surrounded by rhyolite - TERTIARY Older landslide deposits (Pleistocene) matrix; Q, colluvium; R, flow-lay-Lower rhyolite ered rhyolite. Topographic GLACIAL DEPOSITS Dry Union Formation contour interval, 50 feet; thick Brecciated rhyolite Rock glacier (Holocene) gray lines, graded gravel roads Rheomorphic rhyolite of the Elk Horn Ranch subdivi-ROCKS OF THE SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD Till (Pleistocene; Pinedale glaciation) sion. B, Highly irregular blocks CALDERA Nonwelded rhyolite (outlined in orange; dashed RELATIONS MIOCENE POSTCALDERA ROCKS where approximate) of andesite IGNIMBRITE SHEETS AND RELATED ROCKS LAVAS AND RELATED ROCKS **VOLCANIC SEDIMENTARY ROCKS** INTRUSIONS Intracaldera rhyolite fracture fill Ttra Travertine (Miocene?) laharic breccia, enclosed within Lavas and related rocks Intracaldera landslide breccia flow-laminated rheomorphic **Dry Union Formation** rhyolite tuff. Although flow Mixed clast or undivided megabreccia Dry Union Formation, undivided laminated, the rhyolite contains POSTCALDERA Small-phenocryst dacite centimeter-size angular Andesite- and dacite-clast megabreccia ROCKS Hinsdale Formation Dry Union Formation, Precambrian clasts dominant andesite fragments (hiking pole, Plagioclase andesite Plagioclase-andesite-clast megabreccia \sim 0.9 m). *C*, Closer view of Dry Union Formation, volcanic clasts dominant contact (dashed line) between Proterozoic-clast megabreccia SOUTH RIVER **Hinsdale Formation** block of andesite laharic CALDERA Andesite cone breccia breccia and enclosing dense VOLCANIC ROCKS PREDATING BONANZA CALDERA Wason Park Tuff (27.4 Ma)rhyolite that remains fluidal at Rhyolite Conejos Formation, Middle Units OLIGOCENE VOLCANIC ROCKS the contact. Several small fragments of andesite enclosed *Tracy Volcano (<32.5?–33.5 Ma)* Volcaniclastic rocks IGNIMBRITES AND ASSOCIATED ROCKS OF THE CENTRAL SAN JUAN in the fluidal rhyolite are BACHELOR CALDERA COMPLEX circled. PREVOLCANIC ROCKS CALDERA Rocks Erupted from South River Caldera (27.4 Ma) (27.5 Ma) LOWER TERTIARY SEDIMENTARY ROCKS Carpenter Ridge Tuff Tw Wason Park Tuff Tev Conglomerate and sandstone (Eocene?) Rocks Erupted from Bachelor Caldera (27.55 Ma) PALEOZOIC SEDIMENTARY ROCKS Thu Thv Carpenter Ridge Tuff Upper Paleozoic sedimentary rocks Huerto Andesite Nonwelded ignimbrite Sharpsdale Formation (Pennsylvanian) LA GARITA CALDERA Welded rhyolite ignimbrite CYCLE (28.0 Ma) Caldera-filling(?) rocks Kerber Formation (Pennsylvanian) Rocks of La Garita Caldera Cycle (28.0 Ma) Caldera andesite Lower Paleozoic sedimentary rocks Fish Canyon Tuff Leadville Limestone (Mississippian) Olivine andesite and hornblende andesite-dacite, undivided Brecciated and silicified rocks Andesite caldera-wall talus and landslide breccia Bedded breccia and conglomerate Flank lavas Chaffee Group (Devonian and lower Mississipian) Fish Canyon Tuff WESTERN SAN JUAN Volcaniclastic rocks Fremont Dolomite (Upper Ordovician) Welded outflow ignimbrite sheet CALDERAS (28.3 Ma) Upper dacite Harding Quartzite (Middle Ordovician) Nonwelded to partly welded ignimbrite Upper andesite Local Volcaniclastic Rocks of Saguache Paleovalley Manitou Limestone (Lower Ordovician) Plagioclase andesite Lower Paleozoic rocks, undivided Andesite of Lone Tree Gulch Older Ignimbrite Related to Western San Juan Calderas (28.3 Ma) **Small-phenocryst dacite** PRECAMBRIAN ROCKS Twsn Sapinero Mesa Tuff p€a Aplite of Alder Creek Conejos Formation, Upper Units (~30 Ma) **Quartz-xenocrystic andesite** peg Granitoid intrusive rocks, undivided CONEJOS FORMATION. Tuff of Big Dry Gulch Andesite of Lone Tree Gulch (Saguache Valley) Upper units (~30 Ma) Andesite breccia Metamorphic rocks, undivided Tuff of Big Dry Gulch Rhyolite p€u Precambrian crystalline rocks, undivided Debris-flow deposit of Buffalo Pass Campground Debris-flow deposit of Buffalo Pass Campground Rhyolitic sedimentary rocks Distal conglomerate **EXPLANATION OF MAP SYMBOLS** Dacite of Red Rock Canyon CALDERA-RELATED ROCKS PREDATING THE WESTERN AND CENTRAL ——— Contact—Dashed where approximately located; dotted where grada-CALDERA CLUSTERS Dacite lavas tional. Internal contacts (dash-dot) delineate some conspicuous lava LOCAL LAVAS AND VOLCANICLASTIC ROCKS flows or ash-flow cooling breaks within map units. No contact North Pass Caldera Cycle (32.2 Ma) Dacite breccia shown where boundary between map units is uncertain or indefinite Saguache Creek Tuff Sargents Mesa Volcano **Fault**—Dashed where approximately located; dotted where concealed or Nonwelded crystal-poor rhyolite occupied by intrusive rocks. Bar and ball on downthrown side, Tsa \ \ Andesite-dacite lava where movement known Partly to densely welded crystal-poor rhyolite Rawley Volcanic Complex (~33.2–33.8 Ma) NORTH PASS CALDERA Saguache Creek Tuff Low-angle (thrust?) fault—Teeth on upper block CYCLE (32.2 Ma) Bedded rhyolitic tuff Crest of elliptical resurgent dome Bedded rhyolitic tuff Rocks of the Bonanza Caldera Cycle (33 Ma) **Quaternary slump block**—Dashed where approximately located. **Granitoid intrusions** Hachures on downthrown side SOUTHWEST NORTHEAST **Spring Creek intrusion** Lavas and related rocks Fish Canyon Tuff (28 Ma) Volcaniclastic rocks - TERTIARY **Aplitic granite** indicate direction of uplift Unconformity along caldera wall—Dashed where approximately Porphyritic granite Granitoid intrusions located; dotted where concealed Rhyolite tuff Porphyritic granite of Alder Creek **Bonanza** (33.12 Ma) **Turquoise Mine intrusion** Sanidine-bearing dacite Marshall (33.9 Ma) CONEJOS FORMATION, upper lava units Dacite shatter breccia Bonanaza caldera topographic rim—Dashed where approximately (mostly southwest of Bonanza map area) Intrusive andesite located; dotted where concealed. Erosionally modified Granitoid rocks, undivided **Syncline** Small-phenocryst dacite **Eagle Gulch Dacite** Strike and dip of beds Volcaniclastic rocks BONANZA CALDERA Plagioclase andesite ------Intrusions of uncertain age and affinity Inclined CYCLE (33 Ma) Volcanics of Cochetopa Hills (North Pass) Andesite shatter breccia Vertical Intrusions of uncertain age and Bonanza Tuff Saguache Creek Tuff (32 M affinity (precaldera and caldera) Strike and dip of foliation Postcaldera volcanics (Bonanza) (upper andesite, dacite, Porphyry Peak Rhyolite, and other Andesite scoria Plagioclase andesite Rocks of the Marshall Caldera Cycle (33.8–33.9 Ma) Vertical Bonanza Tuff (33 M Postcollapse caldera-filling rocks Postcaldera lavas and volcaniclastic rocks → Trend of lineation—Showing bearing and plunge. Defined by elongate Postcaldera volcanics (Marshall) Dacite lavas, undivided (Sheep Mountain Dacite, andesite, other dacit pumice lenses or flow structures. May be combined with foliation Lake-bed sedimentary rocks (Rawley Andesite, Tbrl FORMATION Small-phenocryst dacite ncludes dacite and rhyolite). Hayden Peak Dacite Outflow tuff Fracture-fill tuff Plagioclase andesite lavas K-feldspar dacite Dacitic tuff (Tfbd) Andesite lavas, undivided Dacite lavas Rhyolitic tuff (Tfbr) ~_____ Rhyolite lava Finely porphyritic dacite lavas Sample location—X-ray fluorescence (XRF) chemical analyses in tables 3, 5. ³⁹Ar/⁴⁰Ar ages shown in millions of years (Ma) on map **Sheep Mountain Dacite** Porphyry Peak Rhyolite Tyap Tyds Tya 2,Tyaq 2 Tyab and in tables 4, 6. Sample abbreviation at end of age: b, biotite; gm, [No lavas preserved?] Volcaniclastic rocks groundmass separate; h, hornblende; no abbreviation, sanidine. Rhyolite of Laughlin Gulch (Table 5, 6 available at https://doi.org/10.3133/sim3394) CONEJOS **Pitch-Pinnacle Formation** Tracy volcano (<32.5?–33.5 Ma) Andesitic rocks FORMATION, **Thorn Ranch Tuff** Upper dark andesite Middle units Densely welded tuff (~33.2–33.8 Ma) Sargents Mesa volcano Breccia cone and spatter XRF and 40Ar/39Ar Non-welded to partly welded tuff Figure 9. Diagrammatic stratigraphic relations between regional ignimbrites and early interme-Hydrothermally altered rock—Areas of conspicuous supergene diate-composition lavas (Conejos Formation), northeast San Juan region. Thin-dashed lines delimit Megabreccia, andesite clasts dominant acid-sulfate alteration, mainly due to dissolution of pyrite, in vicinity locally mapped lava units in relation to associated calderas. Thick-dashed lines (vertical), approx-Rawley volcanic complex (~33.2–33.8 Ma) Megabreccia, clasts of Badger Creek Tuff of subvolcanic intrusions imate age spans of mapped central volcanoes along east flank of the San Juan Mountains. Plagioclase-rich andesite lavas MARSHALL CALDERA Unit (sanidine age, except as noted) Postcollapse caldera-filling rocks Trachydacite Age (Ma)* CYCLE (33.8–33.9 Ma) NORTH PASS CALDERA CYCLE 32.25±0.05 Saguache Creek Tuff **BONANZA CALDERA CYCLE** SAWATCH-RANGE Resurgent intrusions caldera **IGNIMBRITE** Fine-grain granodiorite/andesite (sn, gm) 33.28±0.06 Aplitic granite Late postcollapse lavas CONEJOS 32.66±0.18 Dacite of Hayden Peak (gm) FORMATION, 32.76±0.02 Megacrystic dacite Jacks Creek volcano (~34.5 Ma) Early lavas and proximal breccias Lower units Caldera-fill lavas (tilted) BZ T 33.03±0.03 Sanidine dacite Porphyry Peak Rhyolite 33.04±0.04 PREVOLCANIC ROCKS 33.0-33.3 Andesite-dacite (bio, gm) caldera trachy • Bonanza Tuff **EXPLANATION** andesite 33.05±0.06 Intracaldera Silicic intrusions Bonanza Tuff > TERTIARY 33.12±0.03 West-side dacite X Rawley complex Intermediate intrusions East-side rhyolite (Gribbles Park Tuff) 33.14±0.09 Postcaldera silicic lavas imes Tracy volcano Precaldera central volcanoes Andesite 32.99±0.15 Postcaldera intermed. lavas + Jacks Cr volcano Sargents Mesa volcano (bio, gm) 33.3-33.7 Rawley volcanic complex (gm) 33.73±0.09 Precursor(?) rhyolitic lavas - PALEOZOIC OLDER VOLCANIC ROCKS SiO₂, in weight percent 31.6-33.7 Tracy volcano (sn, bio, gm) Marshall caldera cycle Figure 6. Alkali-silica diagram, showing compositional variations in rocks of the Bonanza map area. Volcanic and intrusive rocks of the Bonanza caldera cycle are modestly more alkalic than those from the preceding central volcanoes (Tracy, Jacks Creek). Postcollapse lavas (bio, gm) 33.4-33.6 Thorn Ranch Tuff 33.93±0.10 34.06±0.15 Aetna caldera, Badger Creek Tuff 34.2-35.3 Pre-Bonanza Jacks Creek volcano (bio, gm) Bonanza Caldera map area (this map) map area (Lipman, 2012) *Ages are normalized to Fish Canyon Tuff at 28.02 Ma Gunnison valley ¹Ar-Ar ages generalized from Lipman and others (2015) Figure 7. A. Summary of 40Ar/39Ar age determinations for igneous rocks of the Bonanza region, illustrating the narrow weighted-mean ages obtained for multiple samples of individual ignimbrites, lavas, and intrusions of the Bonanza cycle. Abbreviations: bio, biotite; gm, groundmass; sn, sanidine. Data from tables 3, 6. B. Eruptive chronology of the Bonanza region shows precursors to eruption of the Bonanza Tuff, including several central volcanoes and Marshall caldera, source of the Thorn Ranch Tuff at 33.9 Ma. Abbreviations: BC T, Badger Creek Tuff; BZ T, Bonanza Tuff; SC T, Saguache Creek Tuff; TR Lake City map area (Lipman, 1976a) **EXPLANATION** West San Juan Central Qal Quaterary surficial deposits Loci San Juan **EXPLANATION** _____ Post-Bonanza ignimbrites Caldera boundary [60+ km] Distance from Bonanza Caldera TR Thorn Ranch Tuff Bonanza Tuff, areal distribution—Dashed 4,000 km³/m.y. 2,000 km³/m.y. GP Gribble's Park/Bonanza Tuff Eagle Gulch Dacite Post-Bonanza lavas—Andesite to rhyolite Bonanza Tuff—Rhyolite to silicic andesite Pre-caldera lavas—Andesite to rhyolite maparea Andesite and dacite (Lipman, 1976c) Sheep Mountain Dacite Thorn Ranch Tuff—Rhyolite to dacite Paleozoic sedimentary rocks map area (Lipman, 2006) (29.0) Precambrian granitic rocks Bonanza caldera—Dashed where approximate; dotted where concealed Ring faults—Bar and ball on downthrown block. Dashed where approximate; Platoro map area Lower Conejo's (Lipman, 1974) Marshall caldera—Dashed where approximate map area East Gulch Tuff **—— –** Wall unconformity (Lipman, 1975) Basin ______ Fault—Bar and ball on downthrown block. Dashed where approximate; dotted where concealed TUFF (33.12 Ma) **←**Ĵ→ Resurgent crest L20 Inclined bedding—Showing strike and dip * Some caldera megabreccia sites 16 Photograph Site—Includes figure number; C, cover. Bar indicates view direction [Eroded/covered] 10 20 30 40 50 KILOMETERS Dike—Jacks Creek volcano 10 20 ← Cross section location—See cross sections in figure 14 Age, in millions of years Figure 8. Age-location-volume plot, showing southward progression of Tertiary ignimbrite-caldera volcanism in the Southern Rocky Mountain Volcanic Figure 10. Generalized geologic map of Bonanza and Marshall calderas, showing major stratigraphic units, structural Field (revised from Lipman, 2007). Colored vertical bars, volumes of individual ignimbrites, scale on left axis (data from table 1); shaded area, increasing Figure 2. Map showing calderas (maroon, purple, green, and brown calderas discussed here; red, others) of the San Juan volcanic region (blue) features, and locations of cross sections (fig. 14). Margin of Marshall caldera (unconformity between caldera-fill and Figure 12. Areal extent of preserved erosional remnants of Bonanza Tuff (modified from McIntosh and Chapin, 2004). cumulative eruptive volume (right axis). Inset, slopes corresponding to different cumulative eruption rates. Abbreviations: AT, Amalia Tuff; B, Bonanza Tuff; BC, Badger Creek Tuff; CP, Chiquito Peak Tuff; CR, Carpenter Ridge Tuff; FC, Fish Canyon Tuff; GP, Grizzly Peak Tuff; LJ, La Jara Canyon Tuff; Bcr, precaldera rocks), dashed where approximately located. Approximate topographic rim of Bonanza caldera inferred from Eastern areas are dominated by crystal-poor rhyolite, while western area consists mainly of crystal-rich dacite. Figure also and location of map area. Dotted lines, inferred locations of caldera margins where concealed by younger rocks. Caldera ages (in parentheses) distribution of intracaldera rocks and from erosionally modified present-day morphology. Rectangular grid, boundaries shows inferred distribution of the eastern outflow of Thorn Ranch Tuff and East Gulch Tuff. GP, Gribbles Park/Bonanza Tuff; are in Ma. Caldera abbreviations: CC, Cebolla Creek; NM, Nelson Mountain; RC, Rat Creek; SJ, San Juan; UC, Ute Creek. Published map areas are rhyolite of Barret Creek flow field; NM, Nelson Mountain Tuff; SC, Saguache Creek Tuff; SM, Sapinero Mesa Tuff; SMT, Snowshoe Mountain Tuff; SP, of 7.5' quadrangle maps. Abbreviations: HH, Houghland Hill; PC, Peterson Creek; SC, Spring Creek. TR, Thorn Ranch Tuff. Sunshine Peak Tuff; TR, Thorn Ranch Tuff; WM, Wall Mountain Tuff; WP, Wason Park Tuff. **BROAD CREST OF RESURGENT DOME** (granitic intrusive rocks exposed just beyond plane of section) SOUTHWEST Feet, above Flagstaff Whale Hill, 12,162' sea level Mountain **EXPLANATION** 12,000 ∠CALDERA RIM Burned Mountain f Alluvial-fan deposits Caldera-floor andesite-dacite (a) CALDERA RING FAULTS g Glacial moraine Near-vertical northeast flank, m Caldera-collapse megabreccia 10,000 resurgent dome d Dacitic Bonanza Tuff r Rhyolitic Bonanza Tuff granodiorite intrusion aplitic granite intrusion a Andesitic lava flows **p€** Precambrian rocks (\sim 2.5 km intracaldera Bonanza Tuff; >1 km postcaldera lavas = \sim 4–5 km total caldera subsidence) ~1.5 km (5,000 ft) Figure 14. Cross sections, displacement? showing structures and stratigraphic relations across Bonanza caldera; locations SOUTH Topographic rim shown on fig. 10. A. South-MARSHALL CALDERA west topographic rim, across South caldera South flank **Gribbles Park Tuff** crest of resurgent dome resurgent dome (Whale Hill), to west margin Feet, above Intracaldera previously of San Luis Valley (segment of Malpais andesite, 33.0 mapped as simple sequence: Rio Grande rift zone) shows Prior intracaldera andesite-dacite-rhyolite, large ring-fault displacethickness, estimated: 300 m Fine-grain andesite Upper Paleozoic (clastic rocks) ments, great thickness of with many fault repeats (Varga and Smith, 1984); Rawley lavas, ~33.7–33.3 Bonanza Tuff, S Sharpsdale/Kerber Formations intracaldera Bonanza Tuff, (Burbank, 1932) now 2.5 km steep dips on flanks of Post-collapse lavas of Marshall caldera resurgent dome, and inferred location of subcaldera D Dyer granitoid intrusions. B. South (mainly andesite) Proterozoic granitic rocks F Fremont caldera margin, showing Thorn Ranch Tuff (intracaldera), 33.9 displacements across ring M Manitou Formation Figure 13. Generalized regional thickness and compositional variations in the Bonanza Tuff. Outflow ignimbrite is mainly early erupted rhyolite to the east, mainly Figure 5. Oblique view of Bonanza caldera area, viewed from the south. Line definitions: (long dashed where approximate, short dashed later-erupted dacite to the west. Intracaldera tuff contains multiple compositional zones and is ponded to thickness of at least 2.5 km, as exposed on west flank of resurgent dome. Intracaldera tuff was previously mapped as a simple andesite-dacite-rhyolite sequence with many fault repeats (Burbank, 1932). Intracaldera tuff where concealed) orange, erosionally modified remnants of Bonanza topographic caldera rim; black, caldera-subsidence ring faults; yellow, Figure 11. Diagrammatic cross section through concealed south margin of Marshall caldera, showing inferred relations of caldera-filling volcanic units. crest of elliptical resurgent dome; green, margin of Marshall caldera. Topographic-name abbreviations: AP, Antora Peak; Bz, town of Bonanza; Possible remnants of the topographic wall are marked by an east-west alignment of paleohills of Precambrian rocks. Post-collapse lavas and volcanithickness was previously estimated at 300 m (Varga and Smith, 1984) but is currently considered 2.5 km thick. A. Photograph showing densely welded intracaldera dacite, FM, Flagstaff Mountain; HP, Hayden Peak; MO, Mount Ouray; PO, Poncha Pass; PP, Porphyry Peak; RM, Round Mountain; SaM, Sargents Mesa; clastic rocks of this caldera cycle are onlapped by lavas of the Rawley volcanic complex, then by younger ignimbrites (Bonanza, Saguache Creek, and with flattened pumice lenses as long as 0.5 m that define a down-dip lineation, east side road above Squirrel Gulch. B. Photograph showing lower rhyolite, densely welded Fish Canyon Tuffs) and interleaved lavas. Ages, million years (Ma); T, Tuff. SM Sheep Mountain; SP, Saguache Peak; UAV, upper Arkansas Valley; UP, Ute Pass; WH, Whale Hill. Imagery from Google Earth (9/24/13). to its base without any intervening tephra deposits, deposited against caldera-wall andesite at Windy Point (above white dashed line). See figure 10 for photo location. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement